Transactions Paper

(Reviewed and Accepted for Publication)

Discussion in Duplicate Due February 21, 1964.

RADIO NOISE STUDIES ON POWER LINES WITH THE CORONAPHONE

J. R. Leslie
Senior Member IEEE

H. O'Beirne
Member IEEE

Both of:
The Hydro-Elec. Pwr. Com. of Ontario
Toronto, Ont., Canada

A paper recommended by the IEEE Transmission and Distribution Committee and approved by the IEEE Technical Operations Committee for presentation at the IEEE Winter Power Meeting, New York, N. Y., February 2-7, 1964. Manuscript submitted November 1, 1963; made available for printing December 4, 1963.

Price: $ .60 To Members
$1.00 To Nonmembers

(10¢ per copy additional if first class mailing desired)

(Minimum Mail Order $1.00)

All Rights Reserved by
The Institute of Electrical and Electronics Engineers, Inc.,
P. O. Box A,
Lenox Hill Station,
New York 21, N. Y.

Litho in USA

Paper No.
64-52

RADIO NOISE STUDIES ON POWER LINES WITH THE CORONAPHONE

J.R. Leslie H. O'Beirne

The exact location of radio interference sources on a power line has been a problem of long standing in the utility field. The difficulties have been such that even today opinions differ as to the source of radio noise on many common types of lines. One of the reasons for this is that corona currents generated at the point of an electrical discharge travel in both directions along the conductor for considerable distances. A radio noise meter responds to these currents for large distances along the line by picking up the induction and radiation fields around the conductors. Thus, localization of the source by this means has been difficult.

This problem is now believed to be solved by the use of the coronaphone described here and shown in Figure 1. The coronaphone operates by detecting the audible sound produced by the corona discharge. The audible sound does not travel along the conductor, but is confined to the immediate area of the source; hence, it may be used to locate the noise source.

This paper reviews the development of the coronaphone; it shows that a correlation between acoustic noise and the radio influence voltage exists. Finally the application to the study of power line corona sources on high-voltage lines is discussed. One observation is important; on operating lines up to 230 kv in voltage, conductor corona has not been found to be a major contributor to the radio noise field either in dry or wet weather. Hardware noise on the contrary is believed to predominate.

A technical description of the coronaphone is given in the Appendix.

DESCRIPTION OF INSTRUMENT

Briefly the coronaphone consists of an assembly of a high-frequency microphone, a parabolic reflector, and an amplifying and metering system The microphone and reflector are designed to have a highly directional characteristic by responding only to sound waves between 10 and 20 kilocycles in frequency. The design is such that the instrument can separate corona sources less than three feet apart at a distance of 100 feet.

The amplifier and detector circuits are designed to operate on the quasi-peak value of the signal, as early studies in 1959 showed that the noise produced was impulsive in character and the quasi-peak detector would give increased sensitivity compared to an average reading detector. Furthermore, this detector corresponds to that used by RI meters.

COMPARISON OF ACOUSTIC AND CORONA PULSES

Initial field tests on the coronaphone in 1959 had shown that as a location device for corona noise, its sensitivity and directivity was

adequate. But to be of greatest value in studying noise sources on high-voltage lines, a correlation with the radio influence voltage (riv) should exist. Could such a correlation be found? The experiments described below were made in order to explore this question.

A few typical corona sources were set up in the laboratory using a NEMA riv circuit and comparisons were made between the radio noise meter and acoustic signals, the latter at a standard distance from the source. Waveforms of the acoustic and electric (riv) pulses were displayed on an oscilloscope.

A close similarity between the two types of signals was found, each corona burst producing a corresponding acoustic pulse. Figure 2 compares waveforms from the noise meter, trace 2, and the coronaphone, trace 3, for a conductor having artificially applied contamination. The conductor used was a short piece of 1/4-inch-diameter aluminum tie-wire with some dirt that had been removed from an aged ACSR conductor adhering to it. The applied voltage was 21.9 kv and the coronaphone was approximately 15 feet from the conductor. The photograph shows corona to be present only on the positive polarity of the exciting voltage. The time scales have been adjusted horizontally to compensate roughly for the travel time of the sound pulse in the air.

The corona and acoustic pulses from a single suspension insulator at 18.9 kv are shown in traces 4 and 5 of the same figure. The riv level was 2000 uv quasi-peak. Both polarities now contribute to the noise (a fact easily noted in field testing because of the change of the sound). Traces 6 and 7 again compare the pulses, but with a 20 per cent increase in voltage across the insulator, with an riv level of 17,000 uv.

The riv pulses were taken using the field intensity position on the noise meter.

The mechanism of noise generation with the insulator unit is different from that on the conductor. A visual observation in the dark shows that the noise is being generated by two rings of small sparks, one jumping vertically across the small air-gap that exists between the top metal cap and the porcelain, and the second jumping radially from the bottom pin to the porcelain. The equivalent electrical circuit of a single insulator unit is therefore almost symmetrical; it does not matter which end of the unit is positive--there is always a metal-to-porcelain air-gap on one side and a porcelain-to-metal air-gap on the other. Hence, as Figure No. 2 shows, both radio and acoustic noise are generated in both half cycles. Furthermore, since the discharge appears as a number of small sparks all round the insulator, many more acoustic pulses occur in each half cycle; this can be seen in trace No. 5 of Figure 2.

The close correspondence which has been demonstrated between the two types of signals has led to a search for a theory relating the two. The technical literature revealed no useful references. The authors would propose that two mechanisms exist which can cause movement of the air molecules. First of all, the air will contain some ionized molecules; being in an electrostatic field, these ions will move. When the discharge takes place, the electrostatic field will suddenly change and the ions will violently change their direction of movement. From this change, an acoustic pressure wave will be propagated in the air, and will be heard as sound.

The second mechanism is caused by the heating effect of the spark discharge. A small column of air along the path of the discharge will be suddenly heated to a very high temperature; it will expand rapidly, thus generating a positive step pressure wave. As soon as the discharge is over, the air will cool again, contract, and generate a negative pressure wave.

From a theoretical analysis of the dynamical properties of a gas a "time of relaxation" can be derived, a measure of the rate at which a gas approaches steady-state conditions after being disturbed. For air at normal ambient conditions, this "time of relaxation" is 0.17 nanosecond. In other words, disturbances in the air movement caused by electrostatic forces or heating can generate acoustic pulses with rise times faster than one nanosecond. As mentioned above, the riv pulses show similar time constants; it seems reasonable to assume that each corona spark discharge will produce simultaneously an acoustic pulse and an riv pulse, both with similar time constants.

Both riv and acoustic pulses are measured with narrow band meters having time constants less than the original pulse time constants. In this respect both types of meters are bandwidth limited. Their quasi-peak responses should be similar.

However, variations in the riv/acoustic ratio may be caused by acoustic shielding and reflection effects due to the proximity of the hardware surfaces which are producing the corona discharges.

CORRELATION OF RIV AND CORONAPHONE READINGS

As noted above, preliminary tests had indicated that a qualitative relationship exists between quasi-peak measurements of riv and quasi-peak measurements of acoustic noise. In a series of tests to investigate this relationship further, a number of paired readings of riv and acoustic noise were taken on a wide variety of hardware items. Thus insulators from a number of manufacturers were tested, including suspension units and pin-type units of various voltage ratings. Wet and dry tests were made, and on the pin-type units, a number of different ties and clamps were investigated. Finally experimental arrangements to simulate noisy conductors and hardware were tested.

The highest voltage that could be used in the laboratory on the test arrangement was 26 kv, which with higher voltage insulators did not generate sufficient noise to make a correlation possible. For the same reason, it was not possible to test a complete suspension insulator string with clamp, though tests were made on individual suspension insulator units. However, the relationship between acoustic noise and riv appeared to be sufficiently constant that application to field surveys seem justified.

Standard statistical techniques of linear regression analysis were used to establish the correlation and also to measure the significance of the differences between correlations for the various types of insulators and hardware.

This relationship varies only slightly for various items of hardware; for a suspension insulator unit, for example it is

$$Riv = 31 + 0.87C \qquad S = 1.5 \text{ db}$$

Where riv is the noise meter reading, db above 1 microvolt

C is the coronaphone reading, arbitrary units, db.

S is the standard deviation at 100 feet.

Similar equations were developed for the other corona sources, using in all cases the arbitrary coronaphone units.

The regression equation for all items tested fell within the band shown in Figure 3. Thus it would appear that the riv level for any item of hardware may be estimated from acoustic measurements without regard for the type of source, to an accuracy of ±5 db, provided that some precautions are taken with regard to the viewing of the source (Table V).

SURVEYS OF OPERATING LINES

The question of prime interest in the field was that of locating the major sources of radio influence on high-voltage lines. Some of the first tests showed that line conductors, except where noticeably damaged, did not give any response on the coronaphone, throughout the length of the several spans tested. These were 230-kv circuits of standard 795 MCM construction. Each support point did however give readings detectable several hundred feet from the towers and the individual hardware items could in most cases be separated. On the 500-kv Coldwater experimental line on the contrary, the suspension points were quiet whereas the conductors all showed a number of specific corona sources along their length. The number was possibly a dozen or so per phase, in a 1/2-mile section. The suspension hardware in these tests was either well shielded, or of the self-shielded type.

With this early experience at hand, an extensive survey of transmission line hardware was undertaken. The average of the readings from each item of hardware at a number of tower locations was obtained. The noise levels were normalized to a standard 100-foot distance from each source, using a simple inverse distance law.

All the riv estimates were then converted by using the regression line represented by the upper edge of the band in Figure 3. This line was obtained from a test arrangement in which an aluminum spike was generating noise, probably a reasonably close approximation to the actual noise mechanisms on a transmission line. The aluminum spike gave higher riv generation for a given acoustic noise than any of the other arrangements; if the average riv figures quoted in the tables are in error, they will probably all err on the high side.

The results of a survey on a 12-year-old 230-kv line are given in Table I. The conductors are 795 MCM ACSR. Some of the measurements were taken on a section with single-circuit steel towers, and some with double-circuit steel towers; the data for both have been combined. The loop support clamp, suspension clamp and dampers appear to be the large noise source. Line voltage was 240 kv. The conductor noise was everywhere below background, and the weather during the tests was fair. The Table lists the mean value, m, and the standard deviation, s. Table II summarizes the field results on the four classes of operating lines which were examined, all tests being in fair weather. Column A repeats the results in Table I.

Column B refers to a new section of 230-kv double-circuit line. This line uses a design of tower with close-circuit spacing, conductors 1843 MCM ACSR, single-bolt torsional dampers. When these measurements were taken, the line had been in service for only one month. The suspension clamps and loop clamps are again the predominant noise sources.

Column C summarizes measurements of a 5-year-old section of single-circuit wood pole line hybrid construction, operating at about 250 kv. The centre conductor is 1192 MCM ACSR with double U-bolt torsional dampers, the outer conductors, 795 MCM ACSR with single-bolt torsional dampers. Phase spacing is 18 feet. A large proportion of the readings were at the background noise level, so statistical techniques for a truncated normal distribution were used.

Some of the data for single-circuit towers are analyzed to find if there is any significant difference between the noise generated on the centre and the outer phases. The centre conductor of this line operates at a 5 per cent higher voltage gradient than the outer conductors. Using the rule-of-thumb that a 10 per cent increase in voltage gradient doubles the radio interference, we would expect about 40 per cent more riv on the centre phase. Of course, these gradients are calculated for the conductors at mid-span, whereas most noise sources will be on hardware close to the tower. Nevertheless, as can be seen in Table III, coronaphone readings clearly showed higher noise generation. These figures indicate that the

acoustic noise on the centre phase averages 3.6 db higher than that on the outer phase. This figure converted to riv represents 50 per cent higher radio noise generation on the centre-phase hardware. This agrees remarkably well with the rule-of-thumb.

Some comparisons were made between the noise generated in dry weather and in wet weather on 230-kv hardware. The conductor, which in dry weather is quiet unless damaged, is found to generate considerable noise in rain. The average increase in acoustic noise, as measured with the coronaphone, is given in Table IV. The suspension clamp is still 11 db (i.e. almost four times) noisier than the adjacent section of conductor.

It is difficult to estimate from the acoustic noise the riv generated, because no longer do we have a single-point noise source; the coronaphone measures the quasi-peak value of the noise generated by a number of independent sources on a length of conductor of about three feet.

Laboratory tests were, in fact, made to show the nature of the response. The reading changed by a negligible amount as the number of sources on a short length of conductor was increased from one to four.

Provided the quasi-peak relationship truly holds, the hardware should thus predominate over the conductor in foul weather. This conclusion is borne out by recent foul-weather ri tests wherein the quasi-peak-to-average ratio on the Stoddart meter does not change from fair to foul weather, on a given line. If the origin of the predominant noise does in fact change in rain from a relatively small number of hardware sources to numerous conductor discharges, one would expect this ratio to change. The argument has great practical value because, if this conclusion is valid, a reduction in the foul-weather ri can be achieved at relatively small cost, by minor changes to suspension hardware designs. Additional study and tests are required, however, before the source of radio noise during precipitation can be determined without question.

The actual ri values estimated from the field tests are close to the values to be expected from under the line ri measurements. Taking the ratio of on-line to under-line noise at 200/1 for a measurement 100 feet out, the ri would be of the order of 50 to 75 microvolts per meter. Actual values are close to this.

115-KV DATA

Readings have been made on 115-kv circuits of various types. A total of 42 samples of suspension insulators with clamps and 54 samples of dampers gave only one reading above background, and that on a damaged insulator. However, the background was unusually high at this time, caused by birds and insects. It can be said that the riv level for each noise source was below 1000 uv.

Some results (Column D, Table II) were obtained at a later date, using the technique of truncated normal distribution. They gave a mean of 31 db (estimated riv = 2800 uv) for 18 samples of suspension insulators with clamps, but noise on 42 samples of dampers was all below background. These results agree with radio interference measurements on the right-of-way where the levels are found to be negligible.

EFFECT OF VIEWING ANGLE

Because some corona discharges might be shielded in the field from direct view with the instrument, tests were made of this effect. Readings were taken on a 230-kv line from eight equally spaced 45-degree points on the circumference of the circle centered on each sample. In Table V, each line represents one sample, the maximum and minimum readings are given.

Two interesting points may be noted. First, the acoustic range is smaller for the suspension insulator with clamp and double U-bolt damper (where the noise source was visible from all angles) than for the other three types of hardware (where the noise source was hidden when viewed from certain positions). Second, it took about 10 minutes to make the eight readings on each item: there is a possibility that the corona discharges fluctuated during this time, adding to the range.

REPEATED READINGS

During the measurements on a 230-kv double-circuit line, readings were repeated on some items six days later under similar voltage and weather conditions, and an analysis made of the differences between the first and second sets of readings. The results obtained are shown in Table VI.

A statistical t-test shows that these differences can be taken as zero, with less than a 5 per cent risk of error in all but the last case. The possibility exists that the line voltage changed between the two sets of readings.

TESTS ON ONTARIO HYDRO'S EHV LINE AT COLDWATER

The first tests of the coronaphone on Ontario Hydro's 600-kv test line were conducted to demonstrate that the coronaphone was a practical device for locating noise sources from a distance, and second to determine which of two microphones was more suitable. In making these tests, the locations of a number of noise sources were accurately recorded and their intensities measured.

Some three months later these same points were checked, again one week later, and again one day later. It was found that of the dozen or so noise sources recorded on each day, many could not be detected on the next

survey; however, new noise sources of approximately the same number had appeared at different locations. The explanation was taken to be that noise was caused by ihsects or by particles of dirt adhering to the conductor, particularly at small scratches or at areas of mechanical damage, and that between observations, these contaminants had either been washed off by rain or burned off.

Some stationary corona sources proved to be due to areas of conductor damage, which were subsequently examined with the line unenergized. In every instance, signs of mechanical damage were found wherever strong noise sources existed on the conductors.

In another test, the acoustic noise generated by a number of artificial corona sources at a series of line voltages was measured with the coronaphone, and a correlation attempted between these readings and the corresponding ri measurements. The results were not conclusive, possibly because the ehv test line is so short that a pronounced standing wave pattern of riv is set up, and hence the level of the ri measured depends greatly on the position of the noise source along the line.

NOISE LOCATION TESTS

One interesting investigation concerned the location of a noisy insulator in a distribution station bus. The insulator was one of a group situated close to a noisy transformer, and although the buzzing from the insulator was easily discernible by ear from the ground, it was difficult to pin-point the source exactly. The coronaphone easily picked out the insulator, identifying it accurately and quickly from its neighbours.

Sources of television interference cannot be detected with the coronaphone, possibly because of the frequency response limitations in the microphone.

CONCLUSIONS

A new method of locating radio interference sources on high-voltage lines and apparatus, by the use of an acoustical detector, has been demonstrated. A reasonable correlation between the riv level and the acoustical signal radiated from a single corona source has been found.

The principal noise source on high-voltage lines operating in the 230-kv class has been found to be hardware; the conductors are relatively quiet. On ehv lines where gradients are closer to the maximum corona-starting values, the conductor may be the predominant source.

The coronaphone should prove particularly useful in the study and field testing of new hardware and conductor designs, in determining their corona properties.

APPENDIX

In the coronaphone, shown in Figure 1, the parabolic reflector is constructed from a 24-inch-diameter radar antenna, with a focal length of 9.75 inches. This reflector is mounted on a tripod through geared pan and tilt controls. A polarized ring sight is mounted at the edge of the reflector to help the operator locate or identify noise sources. The microphone is mounted near the focal point on a bracket rigidly attached to the reflector.

The three microphone characteristics considered most important for coronaphone application are, adequate sensitivity, appropriate frequency response, and low internal-noise level. A condenser microphone measures up well to all these requirements, and was chosen in spite of the fact that a unit of this type requires a polarizing battery and a cathode follower. The model selected has a threshold sensitivity of 4.3 nanobars, a frequency upper limit of 20 kilocycles, and is so insensitive to external fields that its performance is not impaired even directly under a 600-kv test line.

Tests after assembly showed that this microphone-reflector combination gives adequate directionality, the 6-db beamwidth at 10 kc being 4.2 degrees. This directionality is sufficient to enable a skilled operator to locate a noise source 100 feet away with an accuracy of about one foot and to separate sources which are 3 feet apart. The sound absorption by the atmosphere is negligible at these frequencies, in a 100-foot path.

The coronaphone amplifier, filter and meter circuits together with the necessary batteries are housed in the box shown in Figure 1. Transistors are used throughout the amplifier in order to reduce battery requirements, thereby increasing portability. Between the microphone and the first stage of the amplifier is a high-pass filter for the attenuation of the relatively large noise energies of low harmonics of 60-cycle and voice frequencies. The maximum voltage gain of the amplifier is 100,000. The effective frequency response is 10 db down at 1500 and 20,000 cycles. The quasi-peak detector has time comstants of 1-m-sec rise time and 600-m-sec delay. An audible output is provided.

The arbitrary units quoted are based on 0 db = 2×10^{-4} microbar, when the band-pass filters and reflector have been removed from the system.

TABLE I. CORONAPHONE SURVEY ON 230-KV CIRCUIT

	No. Samples	Acoustic Level in db m	s	Calculated riv uv
Conductor, 759 MCM	-	Background		1,500
Clamps - suspension with insulators	295	47	4.1	12,000
- loop support with insulators	28	50	5.0	15,000
- dead end with insulators	56	39	6.0	5,700
Dampers - double U-bolt torsional	531	47	4.3	12,000
- stock bridge	12	40	4.9	6,400
Joints - compression	92	31	10.0	2,900
- repair sleeve	5	26	3.0	1,800

m = mean, s = standard deviation

TABLE II. CORONAPHONE FIELD SURVEYS SUMMARIZED

	A	B	C	D
Tower Type	Steel	Narrow Steel	Wood	Steel
Conductor size MCM	795	1843	1192/759	
Nominal line voltage	230 kv	230 kv	250 kv	115 kv
Corona Source	riv (uv)	riv (uv)	riv (uv)	riv (uv)
Conductors	*	*	*	*
Clamps - suspension with insulators	12000	9300	14000	2800
- loop support with insulators	15000	11000	12000	
- dead-end with insulators	5700	7900	3300	
Dampers - double U-bolt torsional	12000	-	7500	*
- stockbridge	6400	-	-	
- single-bolt damper	-	*	1500	
Joints - compression	2900		17000	
- repair sleeve	1800	-	-	

*Samples of these items were measured, but the acoustic noise was below background. The level of riv generated must therefore be below about 1000 uv.

TABLE III. COMPARISON OF RIV ON CENTRE AND OUTER PHASES

	Number of Samples	East	Centre	West
Suspension clamp with insulator	29	45.47	49.49	45.97
Damper, double U-bolt torsional	58	46.73	50.19	46.66
Averages	-	46.10	49.84	46.31

TABLE IV. INCREASE IN ACOUSTIC NOISE IN WET WEATHER

	Number of Samples	Dry Weather db	Wet Weather db	Increase db
Conductor	12	Background	52.3	Over 17.8
Damper double U-bolt torsional	6	45.2	55.6	10.4
Suspension clamp with insulator	5	48.9	63.0	14.1

TABLE V. EFFECT OF VIEWING ANGLE

	Range Max & Min (db)
Suspension insulator with clamp	51.1 to 49.1 48.1 to 40.6 49.1 to 46.5
Double U-bolt damper	55.9 to 48.6 53.0 to 48.1 50.6 to 41.6 50.6 to 45.6
Compression joint	61.0 to 44.0 37.8 to 33.1 54.2 to 30.0
Dead-end insulator with clamp	53.4 to 35.3 45.8 to 38.3 51.8 to 39.9

TABLE VI. REPEATABILITY OF READINGS

	Number of Samples	Difference Between Paired Readings (db) m	s
Dampers	36	-1.2	4.9
Suspension insulators with clamps	30	-1.3	3.8
Compression joints	6	+3.6	12.9
Dead-end insulators with clamps	4	-8.0	5.2
Loop support insulators with clamps	6	-6.0	2.5

m = mean, s = standard deviation

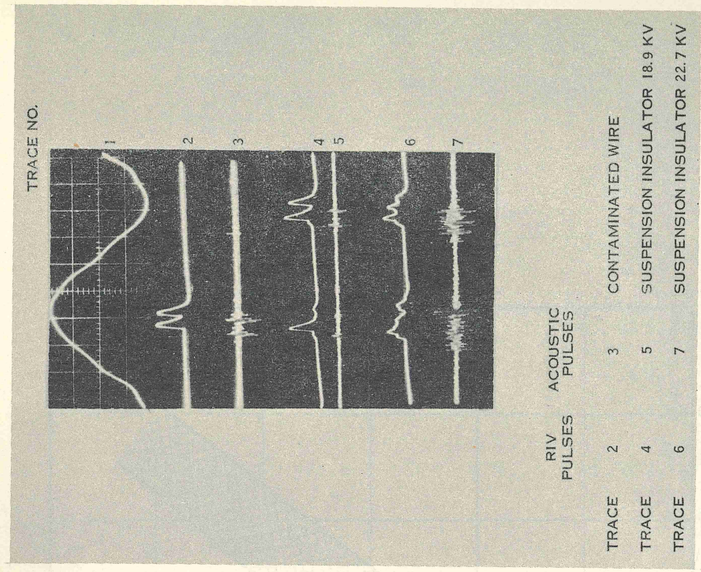

Figure 2. Comparison of Electric and Acoustic Corona Pulses.

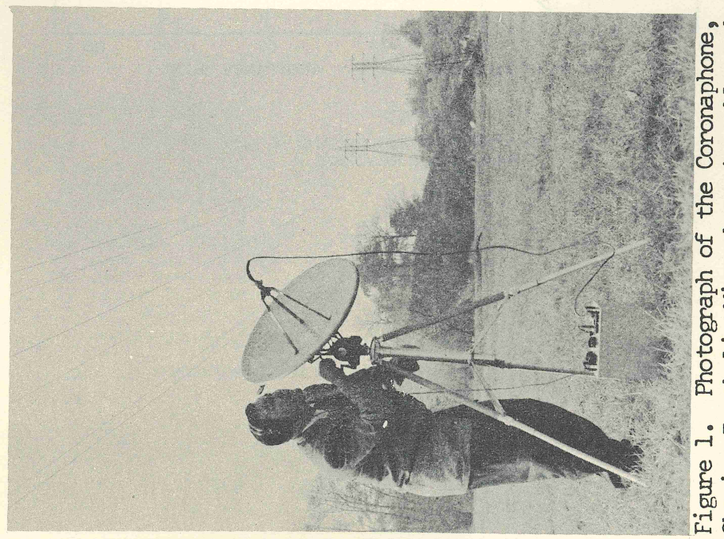

Figure 1. Photograph of the Coronaphone, Showing Parabolic Microphone Assembly and Box Containing Electronic Circuitry and Batteries.

	West
	45.97
	46.66
	46.31

Increase db
Over 17.8
10.4
14.1

tween
s (db)

s
4.9
3.8
12.9
5.2
2.5

Figure 1. Photograph of the Coronaphone, Showing Parabolic Microphone Assembly and Box Containing Electronic Circuitry and Batteries.

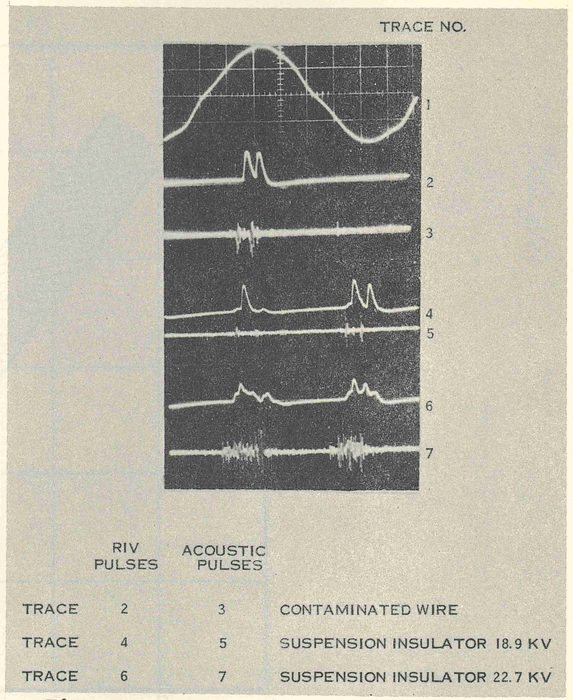

Figure 2. Comparison of Electric and Acoustic Corona Pulses.